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MULTIPIXEL MULTIDIMENSIONAL LASER RADAR SYSTEM THEORY

Final Report

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Massachusetts Institute of Technology

U.S. Army Research Office Contract DAAL03-87-K-0117

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MULTIPIXEL MULTIDIMENSIONAL LASER RADAR

SYSTEM THEORY

Abstract

Coherent laser radars for tactical sensor applications are under development at a number of laboratories, based on the mid-infrared technology of CO_2 lasers and HgCdTe photodetectors. Test bed radars of this class have already demonstrated that tactical targets may be resolved in any combination of the modalities of space, angle, range, and velocity. Under U.S. Army Research Office Contract DAAL03-87-K-0117, a program of research was pursued to advance the system theory of such multipixel, multidimensional laser radars, and to corroborate these advances through experiments performed using the test bed coherent laser radars of the MIT Lincoln Laboratory Opto-Radar Systems Group. Major progress was made on the problem of target detection during the course of this work: quasi-optimal detection processors were derived for various 2-D and 3-D pulsed imagers; performance results for these processors were developed from computer simulation; and 2-D detection performance was confirmed experimentally. Substantial progress was also made on the problem of resolved-target tracking: a generalized Kalman filter was derived for linear-least-squares operation in a track-while-image mode, with tracking performance studied both analytically and through simulation. Finally, a number of ancillary studies relating to laser speckle and atmospheric turbulence effects on laser radar performance were undertaken, including: theoretical treatments of synthetic aperture, range-Doppler, and tomographic laser radars; adaptive optics for large-aperture laser radars; and experimental verification of previous work on laser radar correlation scales.

Research Summary

The development of laser technology offers new alternatives for the problems of target detection and imaging. Indeed, coherent laser radars based on the mid-infrared technology of CO₂ lasers and HgCdTe photodetectors are under development at a number of laboratories [1]–[5]. Test bed radars of this class have already demonstrated that tactical targets may be resolved in any combination of the modalities of space, angle, range, and velocity. Until recently, however, the accompanying theory for coherent laser radar operation has only addressed single-pixel, single-dimensional issues relating to carrier-to-noise ratio (CNR), signal-to-noise ratio (SNR), and range or velocity measurement performance [6]–[11]. Under U.S. Army Research Office Contract DAAL03-87-K-0117, a program of research was pursued to advance the system theory of multipixel, multidimensional laser radars, and to corroborate these advances through experiments performed using the test bed coherent laser radars of the MIT Lincoln Laboratory Opto-Radar Systems Group.

The central foci for this program were determining the limits imposed by speckle and finite CNR on target detection and target tracking using multipixel, multidimensional, laser radar data. For 2-D pulsed-imager operation, quasi-optimal detection processors were derived, and associated performance results were obtained via computer simulation [12]–[14]. These studies produce the first *quantitative* assessment of the trade-offs between multidimensional data collection and detection performance, and their essential features were confirmed experimentally [14]. Quasi-optimal detection processors were also found for 3-D pulsed imagers, and computer simulation used to obtain their performance [15]. Experimental confirmation of the 3-D theory will be sought, along with processor and performance results for target *recognition*,

which is an M -ary hypothesis testing task with $M > 2$ [16]. In the target tracking area, a theory for track-while-image operation of a 2-D pulsed imager was developed, resulting in a generalized Kalman filter structure for linear-least-squares tracking [17]. Tracking performance was studied through Riccati equation evaluations and computer simulation [17],[18].

Additional theoretical studies were undertaken in the areas of synthetic aperture laser radar [19], adaptive optics for large-aperture laser radars [20], and laser radar tomography [21]. The latter two efforts were partially supported by the MIT Lincoln Laboratory Laser Radar Measurements Group. Also, an experimental verification of our earlier work on laser-radar speckle correlations [10] was performed, in cooperation with the Swedish Defense Research Establishment [22]. In what follows, we will survey the results obtained under U.S. Army Research Office Contract DAAL03-87-K-0117; for full details, the reader should consult the publications cited.

Multipixel Multidimensional Target Detection

Our initial efforts to establish the structure and performance of quasi-optimal, multipixel, multidimensional, target-detection processors [12]–[14] led to generalized likelihood-ratio tests (GLRT's) for a full panoply of active-passive, 2-D pulsed-imager detection systems. The receiver operating characteristics (ROC's) for these processors were obtained through a combination of theoretical evaluation and computer simulation, and substantiated through experiments [14], using the MIT Lincoln Laboratory large aperture, multidimensional, laser radar test bed [23]. These studies employed realistic single-pixel statistical models for pulsed-imager intensity and range data, with the latter limited to range-resolution granularity. They assumed a downlooking detection scenario in which the presence or absence of a statistically-uniform, spatially-resolved,

speckle target embedded in a statistically-uniform, spatially-resolved, speckle background is to be decided. Furthermore, the range and angular location of the target—if it is present within the image frame—as well as its reflectivity and that of the background, were treated as *unknown* parameters. A *known* planar background-range profile, and a range-unresolved target were assumed, however.

In more recent work, we have extended the preceding target-detection work in several ways [15],[16]. First, we removed the previous restriction to *coarse-range* (2-D) pulsed-imager operation, by introducing the correct statistical model for *fine-range* (3-D) pulsed-imager operation. Second, we removed the restriction of known background-range profile, by using the estimation-maximization (EM) algorithm to do maximum-likelihood (ML) range estimation [16],[24]. Finally, we used a Markov random field (MRF) range processor [25] to seed the EM algorithm [15],[16]. This approach established a significant tie between MRF processing and statistically-optimum target detection, in that analog VLSI implementations of MRF processing are being proposed for target-recognition applications in next-generation radars.

Laser Radar Tracking Theory

Once a target has been detected, it frequently must be tracked. When an imaging laser radar is used to track a target, we have a multidpixel, multidimensional, *multiframe* system problem. In [17], we completed a first theoretical study of tracking an extended speckle target with a coherent laser radar. This work dealt with a target being tracked in the absence of background reflectors. It developed a generalized Kalman filter for linear-least-squares tracking in the track-while-image mode, and used Riccati equation evaluations to study tracking performance. In [18], we extended the approach used in [17] to account for the same downlooking background scenario employed in our

target-detection work. This study, in addition to obtaining the tracker structure and theoretical performance, has used computer simulation to probe the loss-of-lock issue associated with image-frame boundaries.

Synthetic Aperture Laser Radars

We developed theoretical results for the spatial resolution and carrier-to-noise ratio behavior of the coherent laser radar version of the familiar microwave synthetic-aperture radar (SAR) [19]. This work included the effects of target speckle, laser frequency instability, atmospheric turbulence, and radar/target motion effects. Sample system calculations showed that random vibrations were the most serious limitation on the use of SAR at optical frequencies, but such systems should be feasible with available laser frequency stabilities and typical turbulence strengths.

Adaptive Optics for Large-Aperture Laser Radars

We analyzed the use of wavelength-diversity adaptive optics to compensate for atmospheric turbulence effects on a ground-based, large-aperture coherent laser radar [20]. We showed that as few as two wavelengths could provide very good discrimination of the turbulence-phase component from the speckle-phase component in the return from an extended target.

Laser Radar Tomography

We are completing an investigation [21] of the effects of target speckle on tomographic laser radar imaging [26]. This study comprises a thorough treatment of speckle and CNR limitations of backprojection and filtered backprojection tomographic reconstructions.

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- Mr. Bradley T. Binder - Graduate Student (Ph.D. expected 1991)
- Mr. Thomas J. Green, Jr. - Research Assistant (Ph.D. expected 1992)

Publications

The following journal articles, meeting papers, and theses have been produced under U.S. Army Research Office Contract DAAL03-87-K-0117.

1. D. Park, "High-Resolution Laser Radar Performance Analysis," Ph.D. thesis, Dept. of Elect. Eng. and Comput. Sci., MIT, January 1988.
2. R.H. Enders, "Laser Radar Tracking Theory," Ph.D.thesis, Dept. of Elect. Eng. and Comput. Sci., MIT, October, 1988.
3. D. Park and J.H. Shapiro, "Performance Analysis of Optical Synthetic Aperture Radars," Proc. SPIE 999, 100 (1988).
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13. R.E. Mentle and J.H. Shapiro, "Track-While-Image in the Presence of Background," Proc. SPIE 1471, in press.
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